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Art. VIII.—*Interference Fringes Produced by Scattering and Reflection.*

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Abstract

When a partly-polished optical flat was placed face downwards on a standard flat, and illuminated by a small bright white-light source, the pattern corresponding to the colours of thick plates was observed encompassing the image of the source. When the top surface of the standard flat was aluminized, the pattern was much more intense. A new phenomenon occurred when the pair of plates was illuminated by light from a mercury lamp which passed through a narrow slit, the single pattern giving place to two separate patterns, whose intersections gave the locus of the pattern observed with white light. When the scattering surface was made semi-reflecting, the double set of patterns became sharper, one set being localized in the plane of the scattering surface, the other in planes corresponding to the position of the Newton ring pattern formed by multiple reflections. Various experiments are described for studying these patterns. It is concluded that all three systems of fringes are produced by multiple reflections between the two reflecting surfaces, the assumption of Stokes that the colours of thick plates could only be produced by light passing and repassing the same particle being unnecessary. It is considered that the pattern corresponding to the colours of thick plates is produced by the summation of the intensities of the light from a pair of separate patterns of the simpler Newton ring type, one set being produced by light scattered by the top surface and then suffering multiple reflections between the surfaces before reaching the observer, the other set being produced by light from the source suffering multiple reflections between the plates, and finally being scattered by the scattering centres.

Introduction

When a partly-polished optical flat was placed on a standard flat and illuminated by an electric lamp, it was noticed that an interference pattern which differed from the usual Newton ring pattern was observed surrounding the image of the source. It was also observed that when a bright mercury lamp was used the pattern was resolvable into two systems of fringes of the Newton ring type, the intersections of which produced a pattern similar to the first pattern observed. The double set of interference patterns was sharper and more easily observed when the scattering surface was also made semi-reflecting.

A search of the literature revealed that Newton, Young, Stokes, and others had been interested in interference patterns produced by surfaces capable of scattering light, a phenomenon often discussed under the title "The colours of thick plates." So far as the author is aware, the pair of patterns observed when a monochromatic light source was used has not previously been recorded. The theory suggested to explain these latter patterns lead to a more general interpretation of the theory of the colours of thick plates, so it is proposed to summarize the conclusions reached by some of the previous workers, to describe the experiments that were carried out to obtain the additional system of fringes, and to discuss an explanation for them and for the colours of thick plates.

Earlier Experimental Work on the Colours of Thick Plates

Newton (1) in the fourth part of his second book of Optics described the following experiment. A white opaque card, pierced with a small hole, was placed at right angles to the optic axis of a concave glass mirror which had been quick-silvered at the back. The hole was at the centre of curvature of the mirror and the apparatus was arranged so that sunlight passing through a hole in a window shutter of a darkened room passed also through the hole in the opaque card and fell perpendicularly on to the mirror. A set of coloured rings was observed on the card encompassing the hole, and Newton attributed them to light scattered on entering the glass and then regularly reflected and refracted. He applied his theory of fits to account for the fringes.

In 1755 The Duke of Chaulnes (2) produced similar fringes by substituting in place of the glass mirror a metallic speculum in front of which he placed a plate of tarnished mica. The distance between the scattering surface and the reflecting surface could be readily varied, and he observed the variation in the diameter of the fringes with the distance between the surfaces. He also found that the brilliancy of the fringes produced by Newton's method was increased by breathing on the glass or by spreading over the surface a small quantity of milk and water, which on drying produced a good light scattering surface.

Quetelet (3) described a set of coloured bands that had been observed by Whewell when the image of a candle held near the eye was viewed by reflection in a plane mirror of silvered glass placed at a distance of some feet. Whewell and Quetelet found that it was an essential condition of success that the surface was not perfectly bright and to ensure the production of bands it was sufficient to breathe gently on the front surface of a cool mirror. Instead of vapour, which soon evaporated, Quetelet recommended a tarnish of grease.

Young (4), Herschel (5) and Stokes (6) applied the wave theory to account for the fringes observed by Newton. They assumed that one stream of light was reflected by the mirror and then scattered at the surface, another stream was scattered at the surface and then reflected by the mirror. If the two portions of scattered light coincided in direction they were capable of interfering, bright bands occurring when the retardation of the two beams was an integral number of wave lengths. Stokes came to the conclusion that in order for the two streams of scattered light to be capable of interfering it was necessary that they should be scattered, in passing and repassing, by the same set of particles.

The experiments which will be described later using monochromatic light show that it is possible to observe two systems of fringes. One set is produced by light scattered at one surface and then reflected; the other by light reflected between the plates and finally scattered. The intersections of these two patterns give the positions of the interference pattern studied under the title of the colours of thick plates.

The explanation for the double set of fringes observed when using monochromatic line also accounts for the single system that is observed with white light and this will be discussed later in this report.

Experimental Investigation

If one surface of a glass plate, capable of scattering, transmitting and reflecting light, is placed close to another surface which is capable of reflecting light, one might anticipate that there would be two ways in which an interference pattern could be produced. Consider Fig. 1 (*a*) which represents two glass plates separated by a layer of air. If surface A is capable of transmitting reflecting and scattering light, and surface B of reflecting light, an interference pattern would be observed by reflected light interfering with transmitted light, the final beam being scattered by C. Scattering centre C will be bright when viewed from any direction provided that

$$(n_1 + \tfrac{1}{2})\lambda = 2d \cos\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.$$

where θ is the angle of incidence of the light, n_1 an integer, and λ is the wavelength of the light employed.

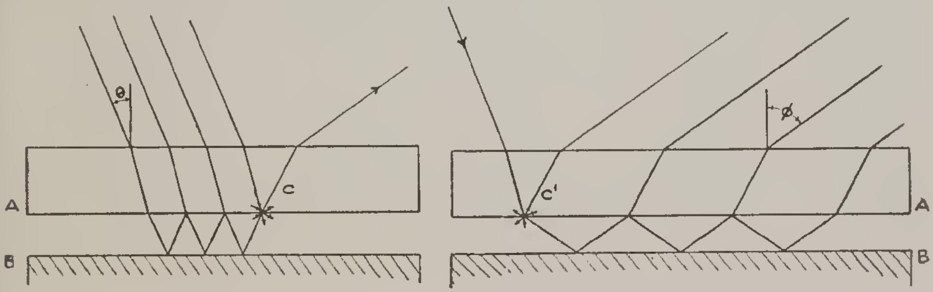


Fig. 1.—(*a*) Production of Set 1 pattern.
(*b*) Production of Set 2 pattern.

The system of fringes represented by formula (1) will be designated as Set 1 in this discussion.

The other system of fringes, which we shall call Set 2, is due to the interference of light that has been scattered from a scattering centre C′ and reflected by multiple reflections from the adjacent surfaces of the glass plates (see Fig. 1(*b*)). Constructive interference occurs when observed at an angle ø, provided

$$(n_2 + \tfrac{1}{2})\lambda = 2d \cos \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.$$

n_2 an integer.

(Set 2 pattern could also be produced by scattering centres on the top surface of the top plate.) The angle of incidence of the light will have no effect on this set of interference fringes other than to vary its brightness.

It was found possible to clearly observe the two sets of interference patterns corresponding to Set 1 into Set 2, using the experimental arrangement of fig. 2.

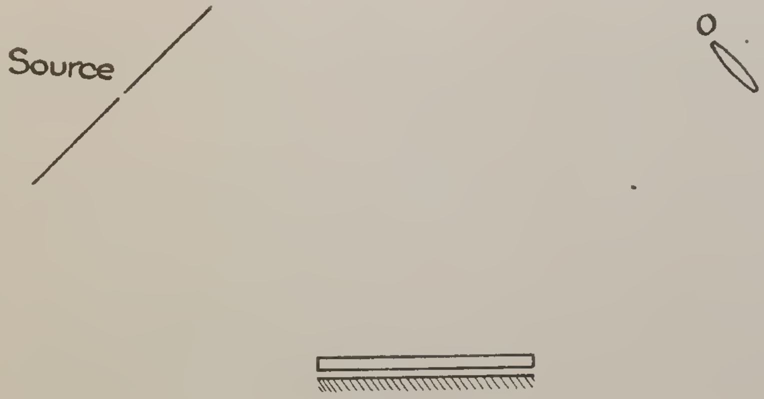


Fig. 2.—Experimental arrangement for studying Set 1 and Set 2 interference patterns.

For this experiment the two plates were optical flats about four inches in diameter. The lower surface of the top plate was made semi-reflecting (half aluminized), the top surface of the lower plate being reflecting (fully aluminized). The scattering points were scratches on the semi-aluminized surface, or were simply produced by spreading a thin smear of oil over the surface with a finger. The surface containing the scattering points was then placed parallel to the reflecting surface of the bottom plate. The flats were placed on the table and illuminated by a mercury lamp. The light from the source passed through a narrow slit (about 2 mm. wide) in a large black card, and the plates were arranged so that the scratched lines or smears of oil were normal to the direction of the light. On observing the reflected image at O it was observed that a double set of interference fringe patterns was visible, the one corresponding to Set 1 fringe pattern being localized in the plane of the surface of the half aluminized plate, whereas the other pattern (Set 2) was localized in a curved surface close to the scattering surface. This latter pattern corresponds to the position of the Newton ring pattern formed by multiple reflections, as given by Feussner (7) and discussed by Tolansky (8). (The double Newton ring pattern due to polarization observed by Tolansky is not resolvable under these conditions.) When one of the glass surfaces used in this experiment was slightly convex, the resultant ring pattern for Set 2 was localized in a regular curve one half before and one half behind the glass surfaces. For an air film the apparent distance D of the fringe from the surface of the plates is given by

$$D = \frac{d \sin \phi}{\alpha} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3.$$

where d is the separation of the plates at the point where the reflection of the light which produces the fringes occurs, α is the angle between the surfaces of the two plates at this point, and ϕ the angle of reflection of the light. Figure 3 illustrates the apparent location of the fringes observed at an angle ϕ to the normal.

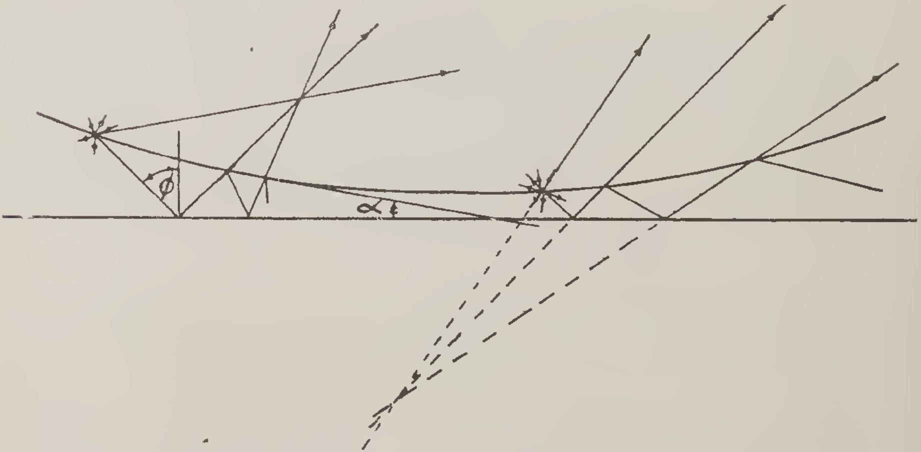


FIG. 3.—Figure illustrating apparent location of fringes for a spherical surface with multiple reflections.

On studying the interference patterns produced, each set could be readily distinguished. When the observer moved, Set 2 pattern moved in the same manner as the usual Newton ring pattern, whereas Set 1 remained stationary relative to the plate. This confirms the interpretation that has been given.

Owing to the different location of the two sets of fringes produced in this manner it was difficult to obtain a clear photograph showing both sets together. Plate III. fig. 1 gives the general effect of the combination of the two patterns. The plates had been tilted so as to form a wedge angle, the two sets of fringes being then approximately straight lines inclined at slightly different angles. The intersection of these systems is clearly seen as bright and dark bands running across the photograph and these will be discussed later.

The double set of interference patterns could also be observed when the top surface was not made semi-reflecting. The patterns were then not as sharp, the effect of half aluminizing the top plate being to increase the resolution of the fringes. The double system of fringes could not be observed when white light was used and this would account for the fact that they had not been observed by the workers mentioned earlier in this report.

A confirmation of the above interpretation of this double set of fringes was obtained by means of the following simple experiment.

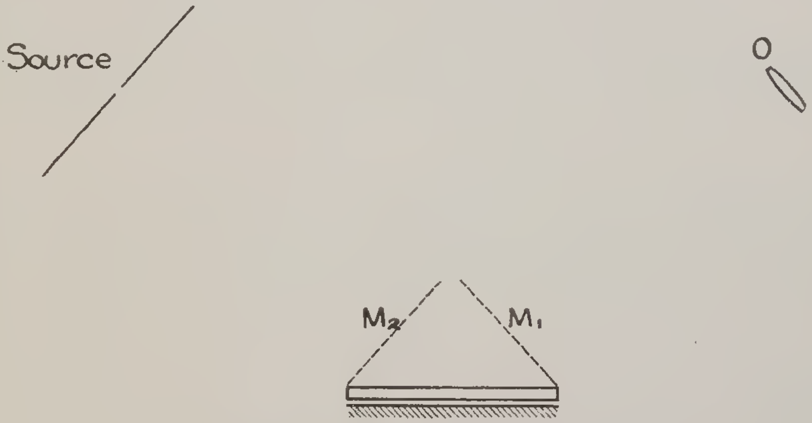


Fig. 4.—Frosted plate at M_1 produces pattern similar to Set 1. Frosted plate at M_2 produces pattern similar to Set 2. Filtered mercury green light with polaroid used.

One surface of an optical flat was made semi-reflecting and this was placed close to the surface of another flat, that surface being a good reflector (fully aluminized). The surfaces were illuminated as in the earlier experiment, the observer being at O. A lightly frosted plate was placed at M_1 (fig. 4) and an interference pattern was observed on the plate. This pattern corresponded to the Set 1 system of fringes. It was slightly enlarged owing to the distance of M_1 from the reflecting surfaces. This pattern did not alter when the observer moved, although it changed when the position of the source was altered. When the frosted plate was moved from M_1 and placed at M_2 the pattern corresponding to Set 2 was observed. (In taking these photographs a polaroid plate was placed before the lens of the camera and rotated until a sharp interference pattern was visible. In this way the doublet system produced by the differential polarization phase change on reflection at a metallic surface is reduced to a single sharp system.) The shape of this pattern varied with the position of the observer but not with the position of the source. These two patterns corresponding to the frosted plate at M_1 and M_2 usually appeared distinctly different, and a typical example of such a pair of patterns is shown in Plate III. fig. 2. With the plate at M_2 the pattern was circular, a single interference colour practically covering the diameter of the plate, whereas with the plate at M_1 the line pattern was observed. Since the pattern with the frosted plate at M_2 corresponded exactly with the Set 2 pattern produce by scattered light at the surface of the plate one can infer that the interpretation given in fig. 1 (*b*) for Set 2 pattern is correct. For the frosted plate placed at M_2 and using surfaces free from scattering centres, fig. 1(*b*) could be modified slightly to interpret this result. Scattering centre C′ would be placed above the top plate at a position corresponding to the frosted plate. A ray from this point making an angle of incidence of ø to the normal would produce a set of rays similar to those shown from scattering centre C′ in fig. 1(*b*). The condition for interference maxima would be given by

$$(n_2 + \epsilon_1)\lambda = 2d \cos \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.$$

where ϵ_1 represents the phase change at reflection from the surfaces. To simplify the discussion we will consider glass surfaces that are not aluminized giving ϵ_1 equal to $\frac{1}{2}$. That is, equation (4) becomes

$$(n_2 + \tfrac{1}{2})\lambda = 2d \cos \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.$$

If the interpretation for Set 2 pattern had been modified by omitting the ray that is scattered back into the glass from C′ towards the observer (fig. 1(*b*)), a system of fringes would be expected corresponding to

$$n_2\lambda = 2d \cos \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 6.$$

assuming again that the surfaces were not aluminized. This formula corresponds to the transmission interference fringe pattern for two parallel plates and it is noticed that it would be displaced one half fringe relative to a system corresponding to equation (5). The ratio of the intensities of the maxima and minima corresponding to equation (6) would be less than for equation (5), the theory being similar to that of patterns corresponding to transmitted and reflected Newton Ring patterns. This displacement of one half fringe between the pattern observed with the frosted plate at M_2 compared with the pattern corresponding to Set 2 is not observed either when the plates are aluminized or when the aluminium layers are removed. We may thus infer that the first ray scattered from C′ back into the glass and thence to the observer is necessary in the interpretation of the Set 2 pattern. It is also assumed that the ray in fig. 1 (*a*) which reaches the scattering centre C without a previous reflection and is scattered to the observer is required in the interpretation of Set 1 pattern. The study of the colours of thick plates confirms this assumption as will be shown later.

THE COLOURS OF THICK PLATES.

When, with the experimental arrangement shown in fig. 1, a white light source was used in place of the mercury lamp, a coloured line pattern was observed corresponding to the intersections of the two systems discussed above. When the plates were parallel, the lines were straight and approximately symmetrical about the reflected image. When one plate was tilted so that a wedge of air was formed, the distances between the lines was greatest where the air separation was least. With this experimental arrangement it was found difficult to obtain clear photographs of this pattern, so another method was used. A pair of plates of suitable size was inserted in place of the prism in a constant deviation spectrometer which had been adjusted for parallel light. One surface of one of the plates was aluminized, and one surface of the other plate carried scratches.

These scratches had been produced by sliding the plate over a sheet of fine emery polishing paper, the motion of the plate being maintained parallel to one edge of the plate. These surfaces were set parallel and close to each other, small pieces of plasticene being used to separate them. The scratches were arranged so that they were normal to the direction of the incident light. With the arrangement shown in fig. 5(*a*) the angles of incidence and emergence are approximately 45 degrees. With the arrangement of fig. 5 (*b*) the angles of incidence and emergence are very small, the separation of the lines for the same distance between the surfaces of the glass plate being much greater. A photograph of the pattern was taken using the arrangement of fig. 5(*a*) and is shown in Plate III., fig. 3 A mercury lamp and green filter had been substituted in place of the white light source, but it will be noticed that even using monochromatic light the lines are diffuse and in the form of broad bands.

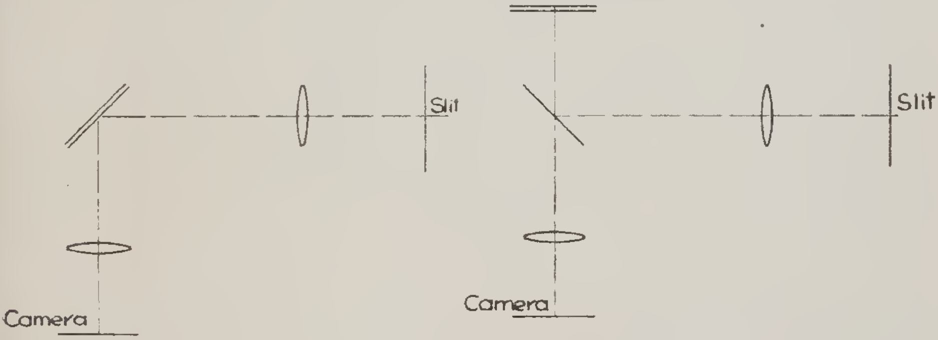


Fig. 5.—(*a*) Experimental arrangement for observing diffraction pattern where separation of plates is small; θ and $\phi \approx \pi/4$.
(*b*) Experimental arrangement for larger separation of plates; θ and $\phi \approx 0°$.

When the lines were ruled at varying distances apart with a ruling engine, so as to maintain constant the depth of the scratched lines, the broad band effect was still evident. A similar pattern was observed when parallel lines were scratched on one surface of a glass plate, the other surface of which was aluminized. These patterns correspond to those previously studied under the title of "The Colours of thick plates."

There are two ways in which we may interpret the production of these fringes. The first follows the lines suggested by the earlier workers.

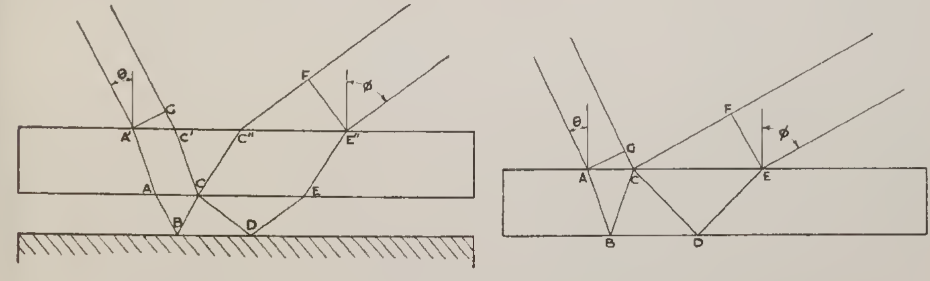


Fig. 6.—Explanation of colours of thick plates, using assumption of Stokes (*a*) air film.
(*b*) single plate.

Let C (fig. 6(*a*)) be one of the lines of the lower surface of the top plate and d the distance between the plates. According to Young and Stokes it would be possible for ray A′ A B C C″ F to interfere with ray G C′ C D E E″. Both rays have been reflected from the bottom plate and scattered by the same scattering centre C. Provided we neglect the differential phase change for different angles of reflection, the optical path difference or retardation is

$$(AB + BC + C''F) - (GC' + CD + DE) = 2d\,(\cos\theta - \cos\phi).$$

Thus interference maxima will occur at angles corresponding to

$$n\lambda = 2d\,(\cos\theta - \cos\phi) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7.$$

where n is an integer.

It is interesting to compare equation (4) with that for the diffraction grating namely $n\lambda = d_1\,(\sin\theta - \sin\phi)$ where d_1 is the distance between the rulings. When $2d = d_1$ grazing incidence spectra for the grating corresponds to normal incidence spectra for the above.

The dispersive power of the system is represented by $d\phi / d\lambda = n/2d \sin\phi$. For small angles of ϕ, $d\phi / d\lambda$ becomes large, which accounts for the increased dispersion using the experimental arrangement shown in fig. 5(*b*) over that shown in fig. 5(*a*).

When the parallel lines are scratched on one surface of a glass plate, the other surface of which is aluminized, the paths of the rays is given in fig. 6(*b*). Here

$$n\lambda' = 2d\,(\cos\theta' - \cos\phi') \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8.$$

where λ' is the wave length of the light in glass, θ' and ϕ' the angles to the normal in glass. This would correspond to the arrangement studied by Whewell and Quetelet.

An alternative suggestion would be for two interference patterns to be produced separately as given earlier. Fig. 7 is drawn to illustrate this possibility, the full lines representing the production of one system (Set 1) and the broken lines the other system (Set 2).

For Set 1 system, i.e. light reflected between the plates and then scattered by C, we have, assuming glass surfaces

$$(n_1 + \tfrac{1}{2})\lambda = 2d\cos\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1.$$

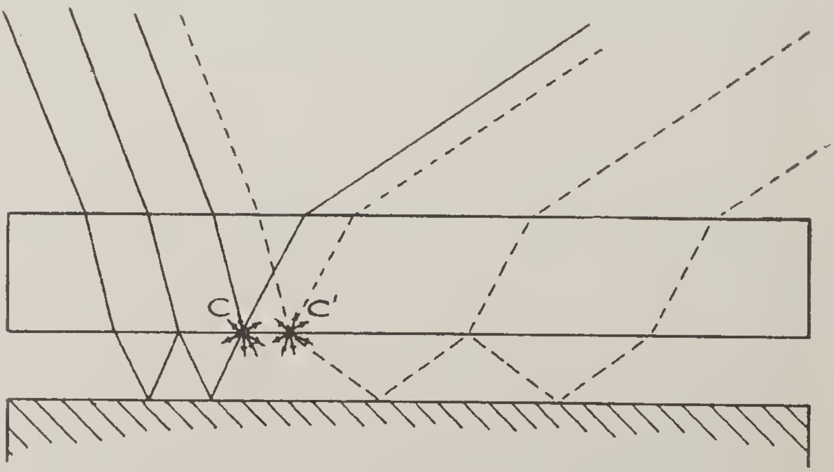


FIG. 7.—Alternative explanation of colours of thick plates.

and for Set 2 pattern, corresponding to light scattered by C′ and then reflected between the plates,

$$(n_2 + \tfrac{1}{2})\lambda = 2d \cos \phi \quad \ldots\ldots\ldots\ldots\ldots\ldots 2.$$

The intersections of these two systems will be given by

$$(n_1 - n_2)\lambda = 2d\ (\cos \theta - \cos \phi) \text{ and}$$

when $n = n_1 - n_2$

$$n\lambda = 2d\ (\cos \theta - \cos \phi)$$

and this agrees with equation (7). It will be noticed that it is possible for the same scattering centre to produce both sets of patterns (Set 1 and Set 2), i.e. for C and C′ (fig. 7) to coincide, and this will cover the original explanation of the production of the fringes if we neglect the possibility of several reflections before and after scattering. We may therefore conclude that the second explanation is a more general one and accounts for the various types of interference patterns produced by scattering and reflection.

It was shown earlier that by comparing the pattern corresponding to Set 2 with a pattern observed when a frosted plate was placed at M_2 (fig. 4), that a ray directly scattered from C′ was necessary to explain the Set 2 pattern. The equation for this pattern was shown to correspond to that of equation (2) above. Since equation (7) for the colours of thick plates correspond to the intersection of the two patterns Set 1 and Set 2 we may, assuming equations (2) and (7), deduce the equation for Set 1. It is found that this corresponds to equation (1). To interpret this equation it is necessary to assume the interference of the rays given in fig. 1(*a*), one ray from the source reaches C without suffering reflections between the plates and is then scattered, whilst other rays are reflected between the plates before being scattered towards the observer.

Stokes affirmed that the pattern corresponding to the colours of thick plates could only be produced by light passing and repassing the same particle. He reached this conclusion as he was unable to observe the coloured pattern when he viewed a luminous point through a plate of glass both surfaces of which possessed scattering centres. An alternative explanation of his result would be that since neither surfaces contained a reflecting layer the intensity of the patterns produced would be low, and the resultant interference pattern difficult to see. The two patterns would also be produced similar to the manner of transmission Newton Ring patterns and for glass surfaces, that have not been made semi-reflecting, these have not the contrast of reflected interference patterns. The coloured pattern corresponding to the colours of thick plates for a white light source has nevertheless been observed by the author on viewing a distant lamp through a glass plate, one or both surfaces of which carries light scratches. A simple way of observing the pattern is to view at night time a distant lamp through a window of a railway carriage. These windows are usually scratched, particularly near the edges, the lines there being reasonably parallel. It is necessary for one surface only to possess the scattering centres, and the interpretation of multiple reflections given above can be simply modified to apply to this case. The pattern can be more clearly seen when the surface of the glass plate is at an angle to the direction of the light, the intensity of the reflected light being then greater than for reflections of normal incident light. The pattern is even more easily observed when a source is viewed through two nearly parallel surfaces that have deposited on them a light semi-reflecting layer, one of which has also been made capable of scattering light.

Conclusion

In concluding it may be stated that by using a source that provides line spectra in place of continuous spectra, for example a mercury lamp in place of sunlight, the study of the colours of thick plates has been made more complete. Two additional sets of interference patterns have been observed and the interpretation of these has suggested a different interpretation from that given previously for the colours of thick plates. To account for the additional sets of interference patterns observed it is necessary to assume several reflections between the two surfaces of glass and the experiments described in this paper have shown that by increasing the number of reflections the resolution of these patterns has been increased. It was observed that the locus of the intersections of these two patterns gives the system previously described under the title of the colours of thick plates. Stokes concluded that it was necessary for two rays to be scattered by the same scattering element in order to account for the pattern observed by Newton. His reason for this conclusion has been discussed and it is shown that an alternative suggestion satisfactorily fits in with the experimental results. It is proposed that the colours of thick plates can be explained as the summation of a pair of patterns of a simpler Newton ring type, which are produced independently, the assumption of Stokes given above being unnecessary.

Explanation of Plate

FIG. 1.—Photograph showing the combination of the two interference patterns to produce the line pattern.

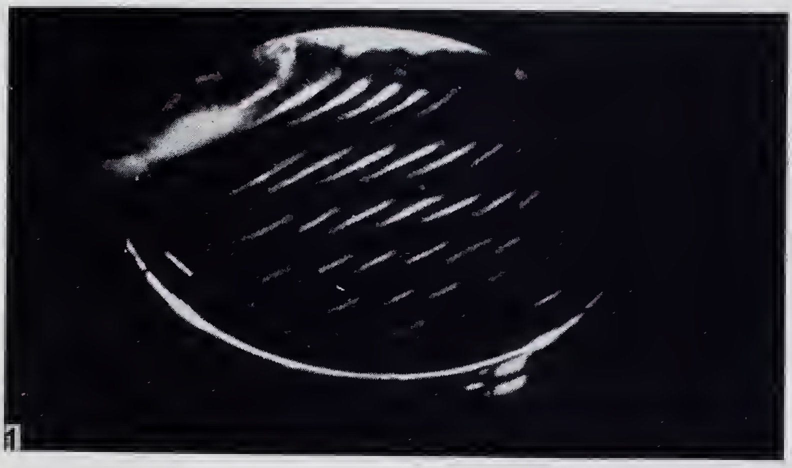
FIG. 2(*a*).—Frosted plate at M_1 (Fig. 4).

FIG. 2(*b*).—Frosted plate at M_2 (Fig. 4).

FIG. 3.—Photograph of pattern obtained using arrangement of apparatus as in Fig. 5(*a*). Separation of plates about 10 μ.

References

1. NEWTON, I.—Second Book of Optics, 3rd Editions (1721).
2. DUKE DE CHAULNES.—Memoires de l'Academie, p. 136 (1755).
3. QUETELET, M.—Correspondence Mathematique et Physique, V., p. 394 (1829).
4. YOUNG, T.—*Philosophical Transactions,* p. 41 (1802).
5. HERSCHEL, SIR J.—*Encyclopaedie Metropolitana,* 676 (Optics).
6. STOKES, G.—*Trans. Camb. Phil. Soc.,* Vol. IX., p. 147 (1851).
7. FEUSSNER, GEHRCKE.—Handbuch der Physik, Optik, Vol. I. (1927).
8. TOLANSKY, S.—*Phil. Mag. Ser.* 7, Vol. 35, No. 241, p. 120 (1944).



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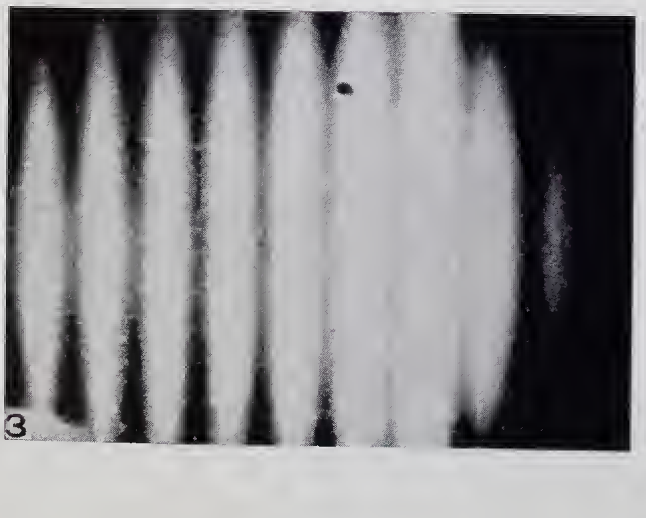

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